A Demonstration of Centimeter-Level Monitoring of Polar Motion With the Global Positioning System

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Daily estimates of the Earth's pole position have been obtained with the Global Positioning System (GPS) by using measurements obtained during the GIG'91 experiment from January 22 to February 13, 1991. Data from a globally distributed network consisting of 21 Rogue GPS receivers were chosen for the analysis. A comparison of the GPS polar motion series with nine 24-hour very long baseline interferometry (VLBI) estimates yielded agreement in the day-to-day pole position of about 1.5 cm for both X and Y polar motion. A similar comparison of GPS and satellite laser ranging (SLR) data showed agreement to about 1.0 cm. These preliminary results indicate that polar motion can be determined by GPS independent of, and at a level comparable to, that which can be obtained from either VLBI or SLR. Furthermore, GPS can provide these data with a daily frequency that neither alternative technique can readily achieve. Thus, GPS promises to be a powerful tool for determining high-frequency platform parameter variations, essential for the ultraprecise spacecraft-tracking requirements of coming years.

I. Introduction

Estimating variations in polar motion, the direction of the Earth's rotation vector with respect to a terrestrial reference frame, has until recently been the province of two space geodetic techniques: very long baseline interferometry (VLBI) and satellite laser ranging (SLR). Reported accuracies from these techniques are typically at the level of 0.3–0.7 mas (1–2 cm),[1] and these techniques generate either 24-hr estimates every few days (VLBI) or 3-day averaged estimates every 3 days (SLR) [1,2]. Requirements by the DSN for pole-position accuracy (one to two weeks after the fact) range from about 5 cm (1σ error)

for the TOPEX mission to under 3 cm for such missions as CRAF/Cassini. Although the non-DSN VLBI data sets that are currently utilized to provide non-real-time polar motion can nominally achieve these goals, two problems may arise. First, the dependence on non-DSN data collection and processing exposes the DSN to the problems, either technical or financial, which these techniques may encounter. Second, the 3–5 day frequency of these other techniques is inadequate to catch rapid variations in polar motion, which still have not been adequately studied.

The Global Positioning System (GPS) has been proposed as an alternative high-precision technique for monitoring pole position at more frequent intervals than those of VLBI or SLR [3,4]. An earlier study [5] demonstrated

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[1] Polar motion values are usually given in milliarcseconds (mas), where 1 mas ≈ 5 nrad ≈ 3 cm at the Earth's surface.

the potential of using GPS to measure polar motion with a sparse global station network and a limited satellite constellation consisting of six GPS satellites. The GIG'91 GPS experiment, performed in early 1991 under the auspices of the International Earth Rotation Service (IERS), employed a large number of GPS receivers distributed worldwide and utilized the 15 available GPS satellites. That experiment provided the first opportunity to test GPS as a competitive technique for monitoring Earth rotation and polar motion [6]. This article presents GPS estimates of the Earth's pole position and its day-to-day variability, and compares these results with those from other space geodetic techniques. The high quality and daily frequency demonstrated by these measurements argue that GPS should be implemented as a standard technique for monitoring high-frequency polar motion variations in support of spacecraft navigation by the DSN. GPS would then serve as a complement to current VLBI techniques, which would remain to provide necessary long-term reference-frame stability and redundancy.

II. Analysis

The first GPS IERS and Geodynamics (GIG'91) experiment was carried out over a three-week period from January 22 to February 13, 1991. It involved numerous international agencies and utilized more than 120 GPS receivers from several different manufacturers with various antenna configurations. A data set was formed from the 21 JPL-developed Rogue GPS receivers [7]. These data were chosen to minimize the effects of antenna phase-center offsets and systematic errors internal to receivers. Moreover, the Rogue receivers provide dual-band P-code pseudorange and carrier-phase data types and utilize a low-multipath antenna. These features were sufficient for robust automatic editing of outliers and carrier-phase cycle repairs, thereby considerably simplifying the GPS analysis [8]. The Rogue receivers were globally distributed, as indicated in Fig. 1, where only the two fixed (fiducial) stations have been labeled explicitly. For a complete list of station names and coordinates, see [9]. Although the station network was global in scope, coverage was somewhat uneven, with 17 receivers in the Northern hemisphere but only four in the Southern hemisphere. Data were sampled continuously at a rate of one point every 2 minutes for most of the Rogue receivers. All the carrier-phase data were subsequently decimated to 6-min intervals, while the pseudorange data were smoothed by using the carrier phase to 6-min normal points.

The GPS data were reduced with the GPS Inferred Positioning System (GIPSY) orbit-determination and baseline estimation software by using two basic strategies:

(1) a standard parameter-estimation strategy with two stations held fixed as fiducials [10], and (2) a variation of the above scheme with no fixed sites, i.e., a free-network strategy [9]. The standard strategy may be summarized as follows: Station locations, satellite states, and carrier-phase bias parameters were estimated as constants. Station and satellite clocks were estimated as white process noise, and the tropospheric delay for each station was estimated by using a random-walk stochastic model. When fiducial constraints were imposed, the station locations of Goldstone (California) and Kootwijk (Holland) were held fixed at coordinates taken from the SV5 reference frame [11]. In addition, the offset of the Earth's center of mass from the origin of the SV5 frame (the geocenter offset) was assumed to be zero.

The location of the rotation axis with respect to a crust-fixed axis (e.g., the IERS reference pole [12]) can be described by two coordinates, polar motion X (PMX) and Y (PMY), where the X-axis lies along the Greenwich meridian and the Y-axis is 90 degrees to the west (both orthogonal to the reference-pole Z-axis), as indicated in Fig. 1. The two pole parameters were estimated daily as constant adjustments to nominal values obtained from the IERS Bulletin B (B37 and B38).

All parameters were simultaneously estimated in a factorized Kalman filter. The satellite states were re-estimated daily to minimize systematic force model errors. The a priori sigmas of most estimated parameters were left essentially unconstrained. Solutions from separate, consecutive 24-hr data spans were computed; hence, pole positions were obtained daily as estimated offsets from the Bulletin-B values.

III. Results

A. Fiducial Versus Free-Network Strategies

Station locations were estimated as constants over the entire 3-week interval, defining a rigid polyhedron for which daily variations of the pole position could be estimated. Solutions were obtained from 22 separate 24-hr periods between January 22–30 and February 1–13. The daily GPS pole-position estimates for PMX and PMY versus time are shown in Fig. 2 and listed in Table 1. The GPS values are estimated corrections to the nominal Bulletin-B values, but the full PMX and PMY values are also shown in Table 1. The open symbols in Fig. 2 correspond to the fiducial case, with two stations fixed (in the SV5 frame). The GPS polar motion series exhibits both an apparent bias and periodic variability with respect to the IERS solution. The mean bias (GPS–Bulletin B) is 2.3 mas (7 cm)

in PMX and 6.7 mas (21 cm) in PMY. In addition to the biases, PMX and PMY exhibit variations of ~5 mas and ~2 mas, respectively, over 5–10 days. Note that the nominal IERS Bulletin-B reference values are themselves derived from smoothed points with 5-day spacing; hence, polar motion variability with a period shorter than ~15 days is not expected to be captured by the Bulletin-B values.

In the free-network case, the fiducial constraints were removed. All station locations were again estimated as constants over the 3-week period, but this time with large a priori sigmas for all stations. The filled triangles in Fig. 2 show the pole positions for this no-fiducial case after a mean offset has been removed. The rms agreement between the fiducial and free-network cases is ~0.03 mas (0.1 cm) for each pole component, which indicates that the fiducial strategy is unimportant for monitoring day-to-day pole-position variability (at least when a global, multi-day rigid network is available). In the free-network case, although the absolute orientation of the rigid network is ill-defined in the sense that it is not strongly tied to a terrestrial reference frame, the relative changes in the orientation of the network from day to day are apparently well determined. The absolute orientation of the rigid network is, however, weakly constrained by finite a priori sigmas (1 rad for PMX and PMY and 10 km for each station coordinate), and by fixed Bulletin-B values for UT1 (not solved for).

B. Consider Analysis

A number of sensitivity analyses [13] were run to determine the effects on pole-position estimates of potential errors in fiducial station coordinates and in geocenter offset. Fiducial errors, at the 1σ level, were assumed to be 3 cm in each of the three station coordinates and 10 cm for each of the geocenter components. These errors are of the same magnitude as the expected accuracies of the fiducial and geocenter positions within the SV5 terrestrial reference frame used to provide the fiducial station coordinates.

The effects on pole position due to these "consider" errors are illustrated in Fig. 3. Shown are the absolute values of the errors in both PMX and PMY averaged over seven 24-hr observing sessions. The root-sum-square (RSS) polar motion error due to errors in the three fiducial components at each site are shown with solid columns. Fiducial location errors on the order of 3–5 cm can apparently lead to pole-position errors at the 1-mas (3-cm) level. The crosshatched columns in Fig. 3 show the error in pole position due to the assumed error in each geocenter component. A 10-cm error in the geocenter can significantly

affect pole-position estimates, as errors in the X- and Y-axis geocenter components generate 2–3 mas pole-position errors. Note that the Z-axis geocenter error has a much weaker effect upon pole errors, which may be understood from geometrical arguments [14]. As seen in Fig. 2, fiducial (geocenter and station-coordinate) errors manifest themselves primarily as constant biases; therefore, they affect the absolute pole position but leave the day-to-day polar variations unaffected.

C. GPS Versus VLBI and SLR Estimates of Pole Position

Solutions from eleven daily VLBI experiments spanning January 23 to February 12 have been obtained [15]. Each solution was obtained from a 24-hr measurement on one of several VLBI networks utilizing typically 4–5 stations. To remove unevenness in network geometries, the station coordinates were fixed at values determined from approximately 1,300 experiments. A concise description of the analysis is given in [15]. Two pairs of solutions were centered only minutes apart; weighted averages were computed for these points so that effectively only nine VLBI pole-position estimates were available for comparison. The VLBI solution epochs occurred at varying times for each daily solution, whereas the GPS epochs occurred at 12:00 UTC each day (obtained from 24-hr solutions running from midnight to midnight). In order to compute the rms differences at the same epoch, the GPS pole-position estimates were linearly interpolated to the times of the VLBI measurements. The GPS and VLBI estimates are shown in Fig. 4, where a mean bias with respect to GPS has been removed from the VLBI solutions for each pole parameter to show the close correlation between the two polar motion series. The resulting rms differences between GPS and VLBI, after removing the mean biases, are 0.4 mas (1.2 cm) for PMX and 0.5 mas (1.5 cm) for PMY. The formal errors for the GPS pole-position estimates are typically 0.3–0.4 mas, while the VLBI formal errors range from 0.1–0.4 mas. Thus, the GPS and VLBI solutions are consistent to within 2σ. The biases between the GPS and VLBI solutions (for the GPS fiducial case, which utilizes the SV5 frame) are −0.1 mas in PMX and −3.2 mas for PMY, where the mean of the (VLBI−GPS) differences has been computed from nine points. Again, these offsets between VLBI and GPS are due mainly to reference frame differences and lie within the error bounds obtained from the consider analysis.

SLR data were obtained from the CSR 91 L 02 series produced by the Center for Space Research, University of Texas at Austin [1,2]. Each data point represents the mean of approximately three days' worth of SLR measure-

ments. The SLR estimates are shown in Fig. 4 together with the GPS and VLBI results, where mean biases with respect to the GPS values have been removed from the SLR solutions to show the close correlation of all three polar motion series. The rms differences between GPS and SLR, after removal of the biases, are 0.3 mas (0.9 cm) for PMX and 0.4 mas (1.2 cm) for PMY. The formal errors for the SLR data average ~0.8 mas; therefore, the computed polar motion series from all three space geodetic techniques are consistent with one another. The mean biases for the (SLR−GPS) differences, computed from eight points, are −2.4 mas for PMX and −5.1 mas for PMY, due most probably to reference-frame inconsistencies.

IV. Conclusions

Day-to-day pole-position estimates spanning 3 weeks have been obtained with GPS by using data from a 21-station global tracking network. The GPS, VLBI, and SLR estimates agree within their formal errors after removing mean offsets, with typical RMS scatter of 0.4 mas (1.2 cm).

GPS fiducial errors do not appear to affect estimates of pole-position variations, but could introduce pole-position biases on the order of 2–3 mas (6–9 cm). Hence, GPS appears to yield polar motion estimates that are at least as precise as those from other techniques, with comparable accuracy as long as the relative biases are accounted for.

Just as significant, the GPS data provide polar motion estimates every 24 hours, and even higher time resolution is emerging from these data [16]. VLBI polar motion is routinely available with a typical spacing of 4–5 days, due to time and fiscal restrictions on the radio telescopes used by the various VLBI networks, while SLR data are only available every 3 days, due to the need to acquire several days worth of data to generate a reliable SLR normal point. GPS techniques do not suffer from either of these restrictions. Thus, GPS can be a powerful complementary technique to VLBI and SLR for monitoring high-frequency pole-position, which can lead to an improved DSN capability for tracking and navigation of future space missions with stringent tracking requirements.

Acknowledgments

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Table 1. GPS pole-position estimates using 2 fixed stations.[a]

Date[b]	PMX[c]	PMY[c]	Full PMX[d]	Full PMY[d]
1/22/91	0.2 ±0.3	5.8±0.4	−50.4	93.1
1/23/91	0.9 ±0.3	5.9±0.4	−52.8	94.2
1/24/91	2.0 ±0.3	6.5±0.4	−54.9	96.1
1/25/91	3.7 ±0.3	6.7±0.4	−56.5	97.6
1/26/91	4.7 ±0.3	6.5±0.4	−58.7	98.7
1/27/91	4.6 ±0.3	7.7±0.4	−62.2	101.4
1/28/91	4.9 ±0.3	7.8±0.4	−65.5	103.0
1/29/91	3.6 ±0.3	7.3±0.4	−70.3	104.1
1/30/91	2.9 ±0.2	7.7±0.3	−74.8	106.0
2/1/91	1.4 ±0.2	7.5±0.3	−84.0	108.9
2/2/91	0.8 ±0.2	6.3±0.3	−88.4	109.2
2/3/91	0.9 ±0.2	6.7±0.3	−91.8	110.9
2/4/91	0.3 ±0.2	6.4±0.4	−95.9	111.9
2/5/91	0.04±0.2	6.7±0.3	−99.7	113.7
2/6/91	1.1 ±0.2	6.3±0.3	−102.2	114.9
2/7/91	1.4 ±0.2	6.1±0.3	−105.3	116.3
2/8/91	1.8 ±0.3	6.1±0.3	−108.3	118.1
2/9/91	2.0 ±0.3	6.1±0.3	−111.3	119.9
2/10/91	2.8 ±0.3	6.3±0.3	−113.6	122.1
2/11/91	2.7 ±0.3	6.2±0.3	−116.8	124.2
2/12/91	3.9 ±0.3	6.4±0.4	−118.7	126.6
2/13/91	2.7 ±0.3	6.2±0.4	−122.9	128.9

[a] Units are in milliarcseconds.

[b] All epochs are at noon UTC.

[c] GPS corrections to the IERS Bulletins B37 and B38 nominal values.

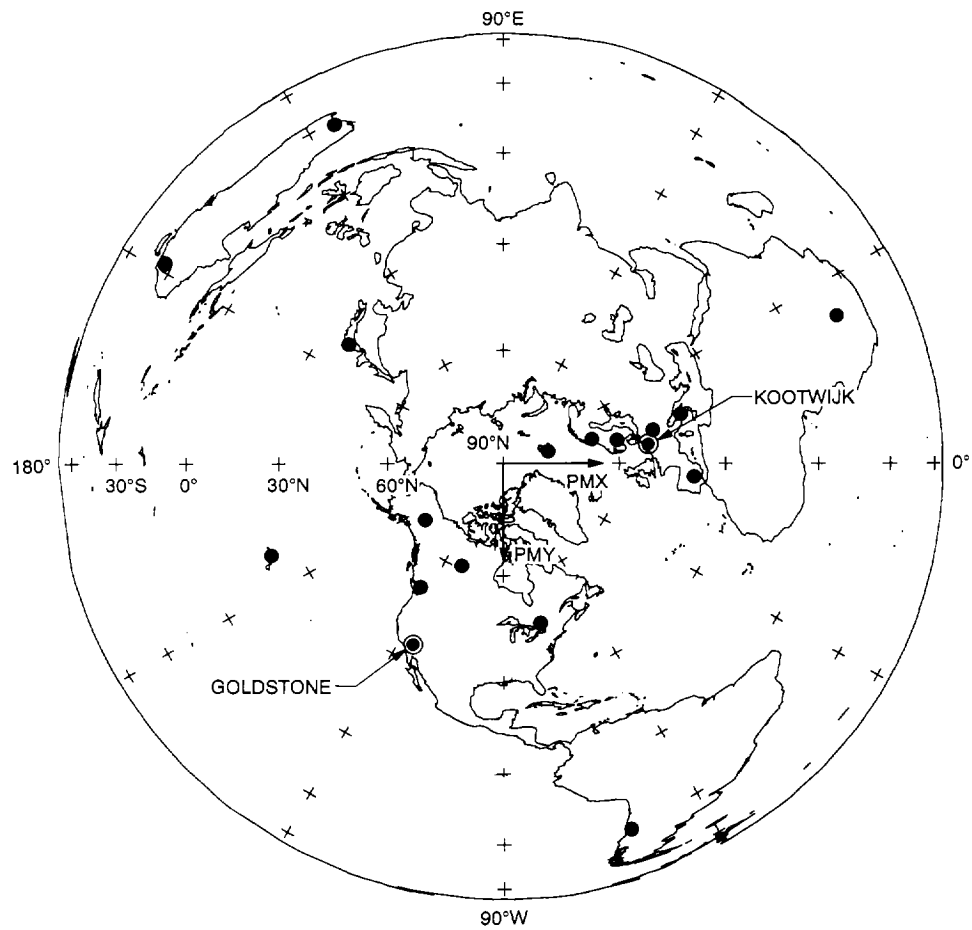[d] GPS corrections added to the Bulletin B values linearly interpolated to noon UTC.

Fig. 1. Shown are 18 of the 21 Rogue sites, distributed worldwide during the GIG'91 experiment (3 additional Rogues in Southern California were also included in the analysis, with fiducial sites labeled).
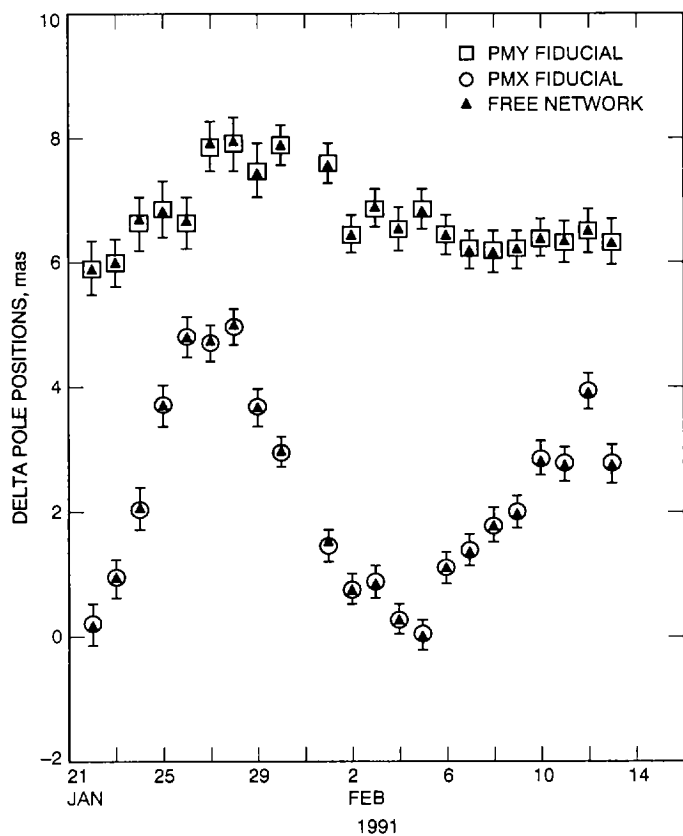
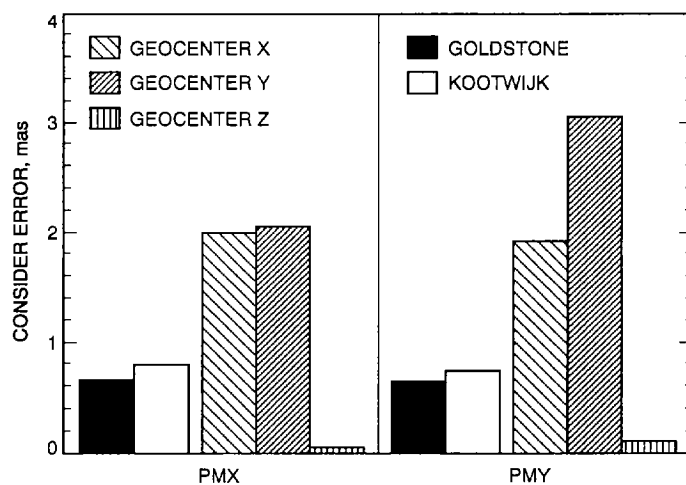Fig. 2. A comparison of polar motion estimates for the fiducial versus the free-network cases.

Fig. 3. Effect of consider errors on polar motion estimates. The solid bars show the consider errors based on a 3-cm error in each fiducial station coordinate, while the cross-hatched bars show the consider errors due to a 10-cm error in each geocenter component.
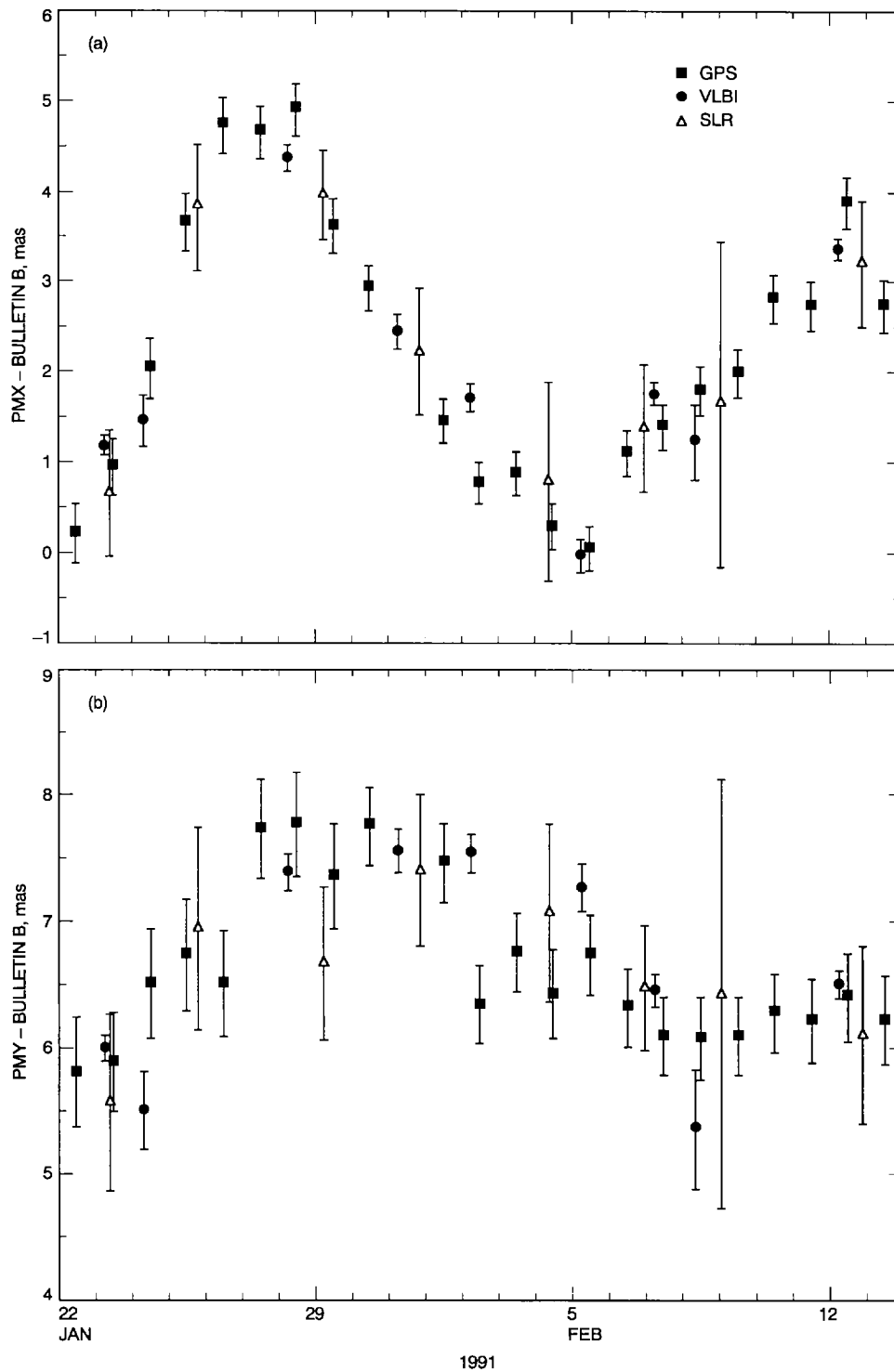
Fig. 4. Estimates of (a) polar motion X and (b) polar motion Y with GPS, VLBI, and SLR, with respect to Bulletin-B values. Mean differences with GPS have been removed from the VLBI and SLR data.